EFFECTS OF AERODYNAMIC CHARACTERISTICS ON THE PILOT'S CONTROL OF THE EXIT PHASE

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INTRODUCTION

The purpose of the X-15 project is to develop an airplane capable of flight at very high altitude and at hypersonic speeds. The lack of flight experience with this type of airplane created a void in the understanding and meaning of wind-tunnel data with respect to flight characteristics. Therefore, a pilot-controlled simulation of the original design proposed by North American Aviation, Inc., flying the exit phase of a typical mission was made on an analog computer. (This original design was referred to as "configuration 1" in a previous paper by Herbert W. Ridyard, Robert W. Dunning, and E. W. Johnston, and is so designated hereinafter.) As a pilot was included in the control loop, pilots' opinion was relied on to a large extent to evaluate the results. In addition to pilots' opinion, selected time histories of airplane parameters are used to illustrate the results.

STATEMENT OF PROBLEM AND ANALOG-COMPUTER SETUP

The primary object of this study was to evaluate qualitatively the aerodynamic characteristics of the airplane with respect to the ability of the pilot to control the airplane. In order to realize this objective it was necessary to use a proposed X-15 flight plan and to represent the airplane as completely as possible.

Figure 1 shows the time histories of Mach number, altitude, and dynamic pressure for the first 160 seconds of a high-altitude flight plan. The unshaded area of this figure is the portion of the flight plan over which these studies were made. This region was selected because burnout occurs approximately halfway through the flight and may introduce violent trim changes. In addition, the variations in Mach number from 3.2 to 5.5, in altitude from 84,000 to 180,000 feet, and in dynamic pressure from 350 lb/sq ft to 20 lb/sq ft provided a wide range of flight conditions over which the pilot must control the airplane.

In this investigation it was assumed that the airplane in flight would follow the variations of dynamic pressure and Mach number of the flight plan. This assumption permitted Mach number and dynamic pressure to be programed as functions of time. Thus, the airplane could be represented by the five-degree-of-freedom equations of rigid-body motion. The aerodynamic data were obtained from the wind-tunnel tests of configuration 1 reported in the paper by Ridyard, Dunning, and Johnston. The section of the high-altitude trajectory selected calls for the airplane to fly at zero angles of attack and sideslip. Therefore, the static stability derivatives were expressed as functions of Mach number for $\alpha = \beta = 0$. As there was a lack of control-surface-effectiveness-coefficient data as a function of Mach number at the time of programing, these parameters were assumed to be constant. The values of these constants were obtained from wind-tunnel tests made at a Mach number of 3.5.

Burnout was accounted for by adding a thrust misalinement of 1 inch, which is the maximum misalinement permitted by the engine specifications, to the pitching- and yawing-moment equations. This 1-inch misalinement corresponds to an out-of-trim moment of approximately 5,000 ft-lb. Figure 2 shows the mass and inertia data obtained from preliminary design reports on the airplane's physical characteristics. These data permitted the mass and inertias to be programed as functions of flight time during burning period. After burnout these parameters remain constant at the lower values.

Figure 3 shows the control setup used. As can be seen, the control setup consisted of a pilot's seat, center control stick and rudder pedals, and a display that replaced the standard flight instruments with cathode ray tubes. While the simulator was operating, the control station was enclosed with canvas screens. The control-stick and rudder-pedal forces were supplied by simple springs and were independent of Mach number and dynamic pressure.

The control-stick and rudder-pedal movement and forces and the corresponding control-surface deflection used in this study are shown in the following table:

Control	Movement, in.	Force, lb	Surface deflection, deg
Horizontal tail	2.5	10	45
Horizontal-tail roll control	4	10	24 total
Vertical tail	1	50	6

Mechanical or electrical stops limited all control-surface deflections at the values shown in the table. The forces and deflections used do not, in the opinion of the pilot, represent good control harmony; however, they were not considered too objectionable. The movie camera shown in figure 3 was used to photograph the pilot's display during the simulated flights. Standard recording instruments were also used to obtain time histories of the significant parameters of the airplane motion from the analog equipment.

Information was displayed to the pilot on three closely grouped cathode ray tubes. The variables displayed were the angles of attack, sideslip, bank, heading, and pitch attitude. These five variables could be arranged as desired, three on the center cathode ray tube and one each on the two auxiliary cathode ray tubes. The first type of display considered presented attitude angles on the center scope and the angles of attack and sideslip on the auxiliary scopes. The pilots found it impossible to fly configuration 1 with this display. A preliminary study of presentation showed that simultaneous presentation of β and ϕ on the same scope was necessary to control the directionally unstable case.

This result led to the display shown in figure 4, the β-ϕ display, which was used throughout most of the study so as to give a more quantitative comparison of the directionally stable and unstable cases. The center scope presents roll attitude and the angles of attack and sideslip by the motion of the inverted T. This marker may be thought of as the rear view of the airplane. The inverted T rotates to present roll attitude and shows the angles of attack and sideslip by vertical and horizontal displacements, respectively. The scales for the angles of attack and sideslip are 6° per inch; negative sideslip is shown to the right. The auxiliary scope at the top of the center scope presents heading and the one on the left presents pitch attitude. The scales for these scopes were 20° per inch. After operating this simulator, the test pilots stated that it constituted a reasonable representation of the task of flying an airplane.

The pilots' task was to maintain the angles of attack, sideslip, and roll to zero. Because of the programing of Mach number and dynamic pressure, this assigned task, if perfectly executed, caused the airplane to fly the programed portion of the flight plan. Each flight was divided into two parts. The first part consisted of a constant Mach number flight at 84,000 feet to trim the airplane at the correct climb angle. When trim conditions had been established the flight over the programed part of the trajectory was made.

Pilots' opinion was used to evaluate the effect of changes in airplane characteristics on the flyability of configuration 1. In general, the opinion of two experienced engineering test pilots was obtained for major changes in airplane characteristics.

PRESENTATION OF RESULTS

Wind-tunnel data indicated that the directional stability parameter C_{n_β} (see fig. 5) might be critical. The value of C_{n_β} for configuration 1, shown by the solid line, changes sign at a Mach number of 4.5, making the airplane directionally unstable. The dashed curve shows the upper limit of C_{n_β} used which gives directional stability throughout the Mach number range considered. Other values of the directional stability parameter between these two limits were tried, including one that approximated the full-wedge vertical tail. Results are presented herein for the two curves shown in this figure.

As the pilot's task was to control the airplane so that α, β, and ϕ were held to zero, these quantities were of primary interest. The results of this study are illustrated by the recorded time histories of α, β, and ϕ.

Figure 6 shows the time history of configuration 1 flying the programed part of the trajectory. The airplane becomes directionally unstable during this run and there are no damping and no disturbance moments. Even though the airplane is rolling, sideslipping, and oscillating in angle of attack, the motions appear small and are not representative of the difficulty encountered by the pilot in controlling the airplane. This successful flight was obtained only after several unsuccessful practice flights had been made. The pilot stated that he had to exercise extreme concentration and mental effort to control the airplane and considered it unflyable. In order to illustrate the critical attention required to control the airplane, this flight was repeated and the pilot's view of the display was obscured for 2 seconds to simulate distraction of other tasks. Figure 7 shows this flight. The time of the coverup is indicated by the solid bar in the figure. As can be seen, shortly after being distracted the pilot loses control of the airplane; that is, all three quantities diverge. In order to show the effect of increased directional stability, C_{n_β} for configuration 1 was increased as shown by the dashed line in figure 5. A flight was made during which the pilot was again distracted. This flight is shown in figure 8. The distraction is again indicated by the bar in the figure. As shown, the distraction caused the pilot to have a little more trouble controlling the airplane than previously, but did not cause him to lose control of the airplane. The pilot felt that with the increase of directional stability the task of controlling the airplane was easier but that damping should be added to the airplane.

No damping derivatives were available for this airplane when the problem was programed; therefore, estimates of the rotary damping derivatives in pitch, roll, and yaw were made and added to the simulation. The damping supplied by these rotary damping derivatives proved completely inadequate, the pilot noting only negligible improvement in the control task. Three-axis auxiliary damping was added to the simulator by feeding the angular velocities back to drive the control surfaces. These feedback gains were gradually increased so as to provide increasing damping, until the pilot felt the necessary minimum damping requirements had been provided.

The next two time histories (figs. 9 and 10) compare the airplane motions with and without three-axis auxiliary damping. In both flights the airplane has increased C_{n_β} so that it is directionally stable at all times. The engine thrust misalinements in the pitching- and yawing-moment equations are included for the first time. A warning as to when burnout was to occur was given the pilot by a signal lamp. At 2 seconds before burnout the lamp was lit and at burnout the lamp was turned off. The marker bar in figures 9 and 10 shows the operation of this lamp.

In the first of these time histories (fig. 9) there was no auxiliary damping. It can be noted that the pilot had considerable difficulty in maintaining control when burnout trim changes take place. It is of interest to note the effect of altitude on the records. At the start of the climb the periods of the motions are very short, while toward the end of the flight the period lengthens considerably. This lengthening of the periods eases the pilot's control task.

Figure 10 shows this same run except that three-axis auxiliary damping has been added to the simulation of the airplane. This damping gives times to damp to half-amplitude of 0.9 and 0.5 second in the Dutch roll and damping-in-roll modes and 0.75 second in the longitudinal mode. While the oscillations are still discernible, the motions are much smoother and the pilot has less trouble holding the angles of attack and sideslip at zero. As shown, the pilot has little difficulty in controlling the airplane when the burnout disturbance occurs. The pilot stated that both the increased directional stability and added damping provided the necessary minimum stability requirements to fly the part of the trajectory simulated.

In order to determine which damper was critical, various combinations of pitch, roll, and yaw damping were studied. The pilot stated that pitch damping appeared more critical than damping about the other axes.

During this simulation, the effect of variations in the rolling moment due to the vertical-tail deflection and the yawing moment due to differential horizontal-tail deflection on the control task were investigated. In the case of rolling caused by vertical-tail deflection, the pilot found this rolling objectionable and he thought it should be kept as small as possible. The effect of yawing due to the differential deflection of the horizontal tail was not as obvious, the pilot noticing little difference between favorable and unfavorable yaw caused by use of the roll control. The pilot felt that both of these parameters had a secondary effect on the control task.

Figure 11 shows the variations in the effective-dihedral parameter C_{l_β} considered in this simulation study. The solid line is the basic effective dihedral for configuration 1 and the dotted and dashed lines show the limits of positive and negative dihedral considered. Small effective dihedral (that is, near zero) was the preferred value; as the effective dihedral increased either positively or negatively, the pilot noted a gradual deterioration of the control problem. The pilot was able to control the airplane for all values of effective dihedral between the limits shown in figure 11. He considered effective dihedral to have a secondary effect in the control task.

In order to obtain some appreciation as to the effect of display on the pilots' opinions of flying qualities and the control task, some simulator runs were made with a more conventional display that presented the attitude angles on the center scope and the angles of attack and sideslip on the auxiliary scopes. In each of the cases shown in the time histories, the pilot felt the control task was more difficult for the display with the attitude angles on the center scope. In order to illustrate the effects of information arrangement, the time histories of figures 12 and 13 have been included. Figure 12 is the time history of a flight with the β-ϕ display, and figure 13, a flight with the attitude display. The airplane configuration in both flights was the same, having directional stability and a high ϕ/β ratio. The figures show that with the β-ϕ display the pilot has little trouble completing the flight; however, for the attitude display the pilot loses the airplane at approximately the time of burnout. In addition, it was found that the effective-dihedral parameter, which was of secondary importance for the β-ϕ display, became critically important to the control task when the attitude display was used. These results, which are of a preliminary nature, indicate that those quantities which are of primary importance to the control task should be presented to the pilot so that the scanning requirement and data assimilation time are a minimum.

CONCLUDING REMARKS

Configuration 1 is considered by the test pilots to be unflyable because of the extreme concentration and mental effort required to control it. The test pilots considered directional stability and three-axis damping very desirable and with both of these added considered the airplane to possess the necessary minimum stability requirements to fly the programed part of the flight plan. The investigation of effective dihedral showed that it had a secondary influence on the control task when the β-ϕ display was used, whereas it had a primary influence on the control task when the attitude display was used. These simulation studies are being extended to other regions of the flight plan.

A HIGH ALTITUDE FLIGHT PLAN

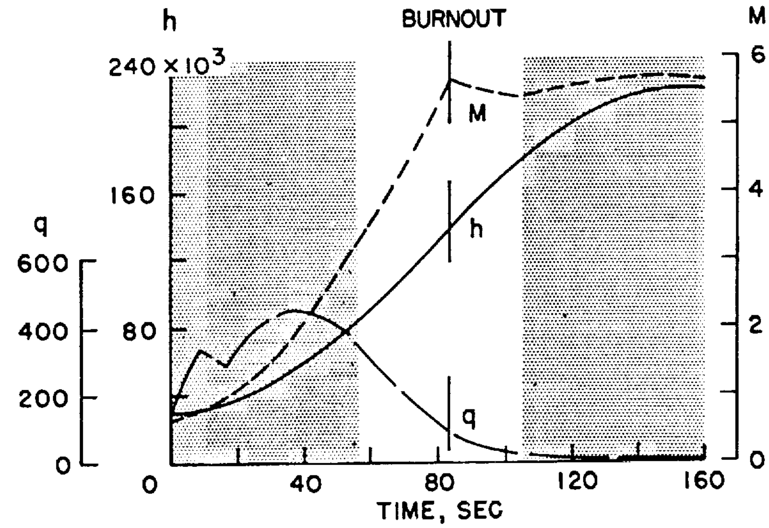

Figure 1

VARIATION OF MASS AND INERTIAS WITH FLIGHT TIME

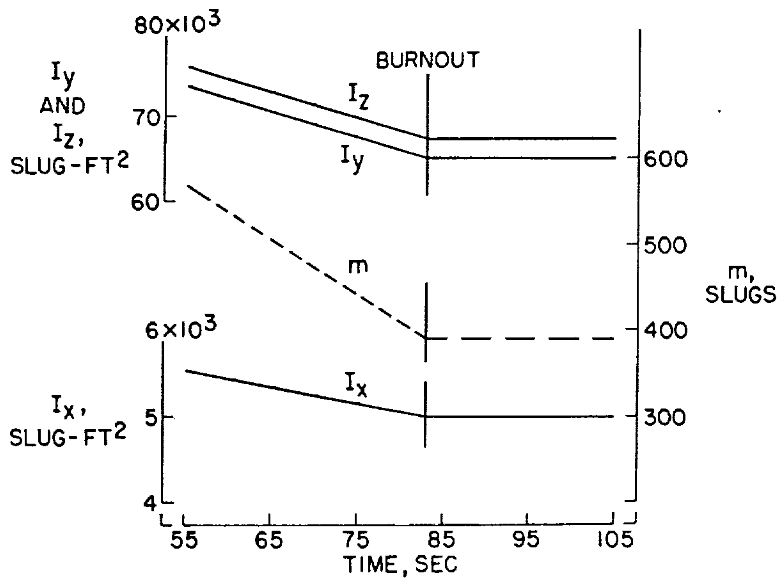

Figure 2

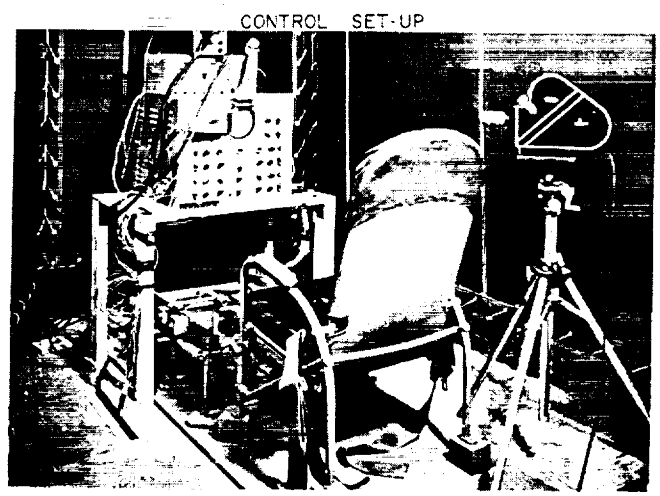

Figure 3

SKETCH OF SCOPE PRESENTATION TO PILOT

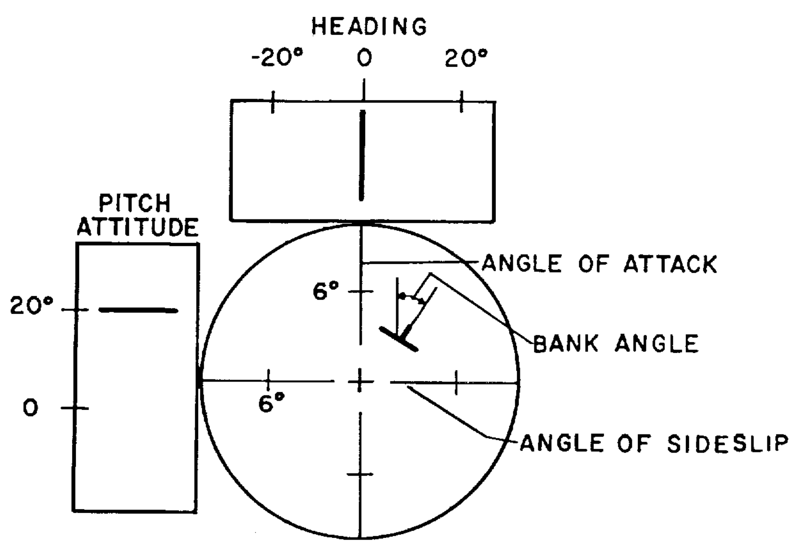

Figure 4

[redacted]

VARIATION OF C_{l_β} WITH MACH NUMBER

$\alpha = 0°$

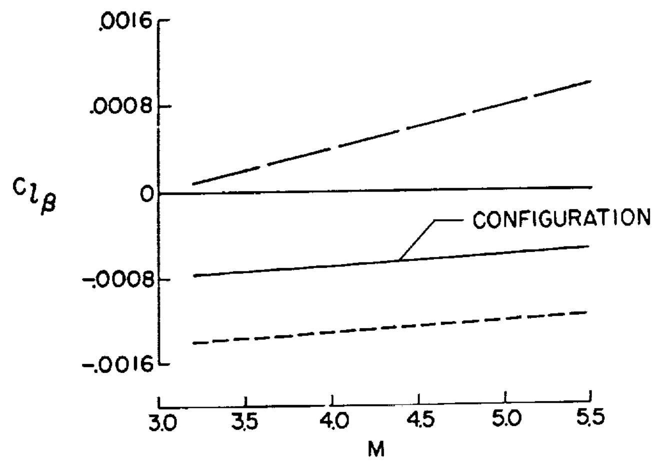

Figure 5

CONFIGURATION I

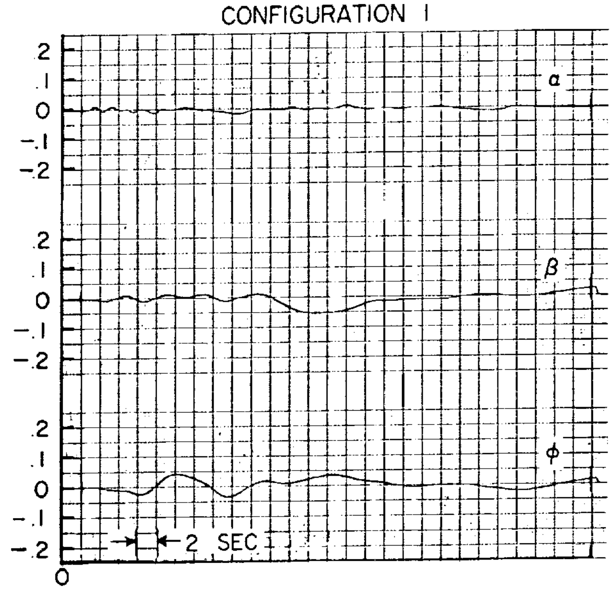

Figure 6

[redacted]

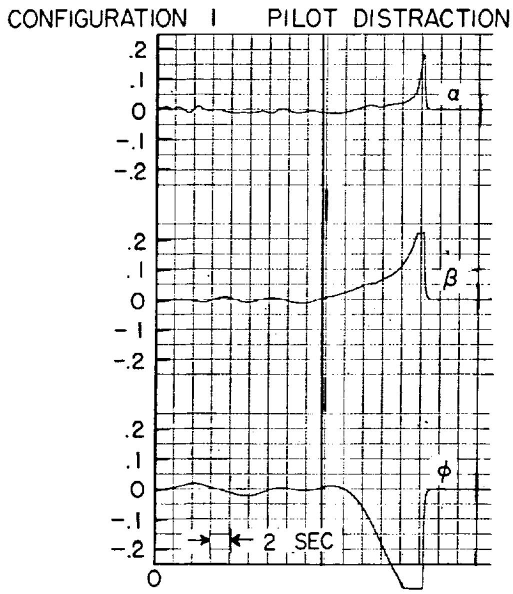

Figure 7

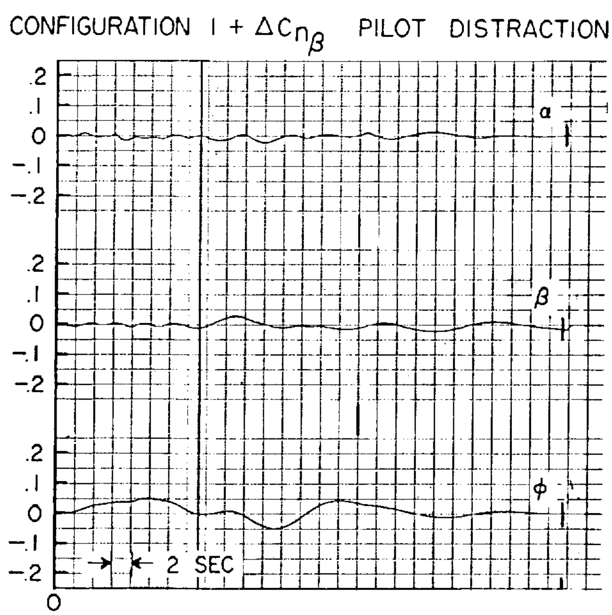

Figure 8

[redacted]

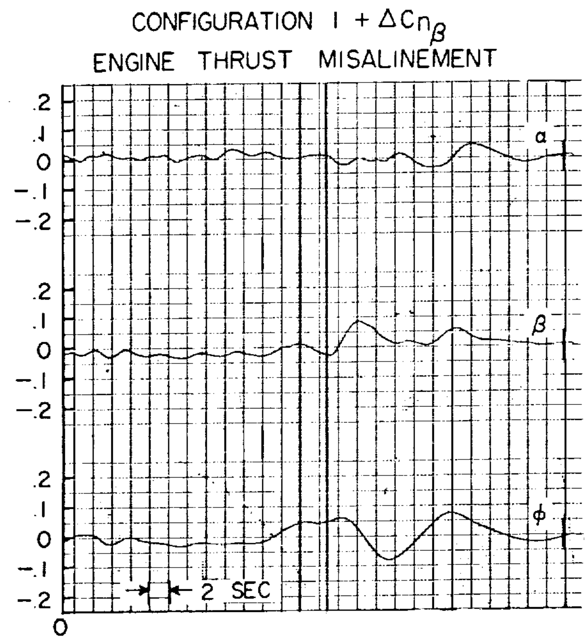

Figure 9

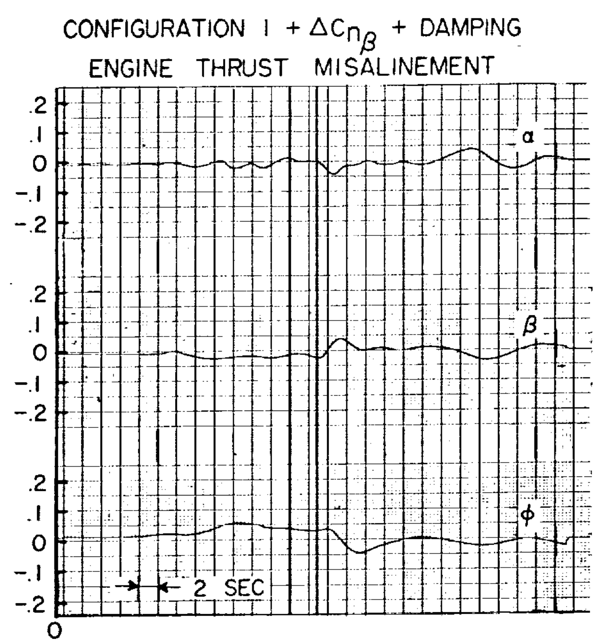

Figure 10

[redacted]

VARIATION OF C_{n_β} WITH MACH NUMBER

$\alpha = 0°$

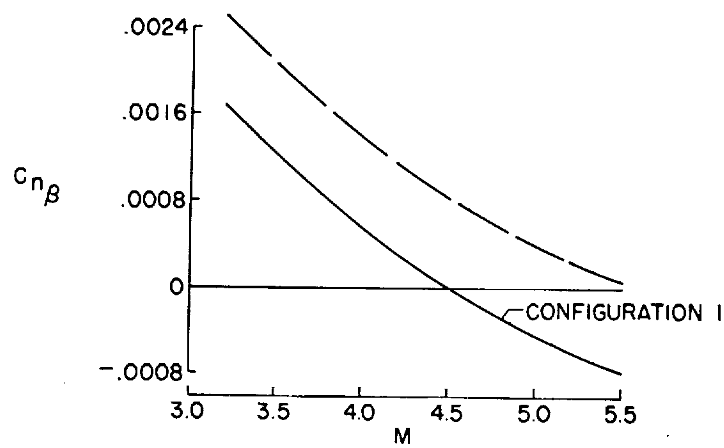

Figure 11

CONFIGURATION I + ΔC_{n_β} + ROTARY DERIVATIVES $\beta - \phi$ DISPLAY

ENGINE THRUST MISALINEMENT

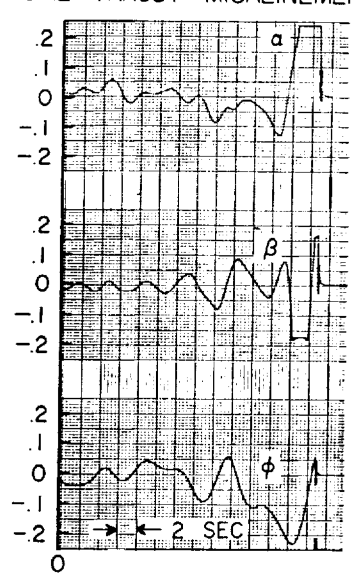

Figure 12

CONFIGURATION I $+ \Delta C_{n_\beta}$ + ROTARY DERIVATIVES,
ATTITUDE DISPLAY ENGINE THRUST MISALINEMENT

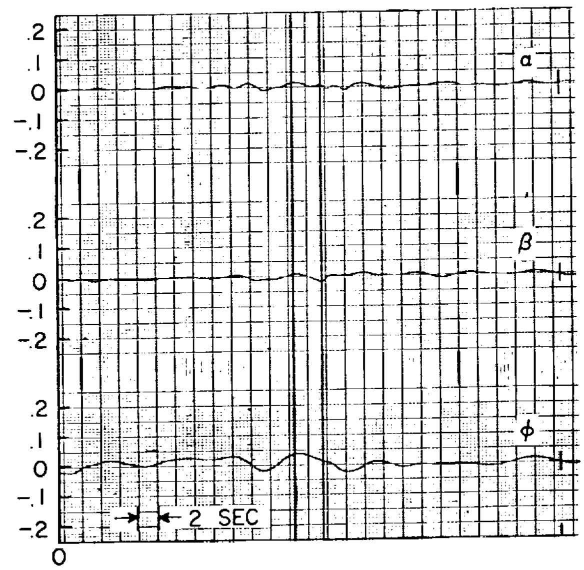

Figure 13